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A performance analysis of a novel system of a dual loop bottoming organic Rankine cycle (ORC) with a light-duty diesel engine

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HIGHLIGHTS

- ▶ The waste heat characteristic of a light duty diesel engine is analyzed.
- ▶ A dual loop ORC is designed to simultaneously recover waste heat of exhaust, intake air and coolant.
- ▶ Effective power and bsfc of combined system is improved greatly over engine's operating region.

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ABSTRACT

A small-scale organic Rankine cycle (ORC) can be used to harness the waste heat from an internal combustion engine. In this paper, the characteristic of a novel system combining a vehicular light-duty diesel engine with a dual loop ORC, which recovers waste heat from the engine exhaust, intake air, and coolant, is analyzed. A high temperature loop recovers the exhaust heat, whereas a low temperature loop recovers the residual heat from the high temperature loop and the waste heat from both the intake air and the coolant. A performance map of the light-duty diesel engine is created using an engine test bench. The heat waste from the exhaust, the intake air, and the coolant are calculated and compared throughout the engine's entire operating region. Based on these data, the working parameters of the dual loop ORC are defined, and the performance of the combined engine–ORC system is evaluated across this entire region. The results show that the net power of the low temperature loop is higher than that of the high temperature loop, and the relative output power improves from 14% to 16% in the peak effective thermal efficiency region and from 38% to 43% in the small load region. In addition, the brake specific fuel consumption (bsfc) of the combined system decreases significantly throughout the engine's operating region.

1. Introduction

Huge amounts of energy are consumed by internal combustion engines in all types of vehicles, with much of this energy is wasted through the exhaust, the intake air, and the cooling systems. Exacerbating this problem is the fact that these combustion products also cause serious environmental issues. Engine waste-heat recovery could improve the fuel thermal efficiency, minimize fuel consumption, and reduce engine emissions. Using an organic Rankine cycle (ORC) to recover the low-grade wasted heat from these systems is the technology that is the closest to being suitable for mass production. When designing an ORC, special attention must give to the choice of the working fluid and the design of a suitable expander [1–7]. Many researchers have investigated ORC system design and parametric optimization. The dynamic performance and control strategy was investigated by Ref. [8] using a time-varying model. The results indicate that the steady-state optimization of ORC under various conditions is very important. The parameter optimization and performance comparison was also conducted by Ref. [9] for low-temperature heat source (80–100 °C). When an engine is running, the energy and exergy quantities of the exhaust, the intake air, and the coolant are significantly different. Because of these differences, it is very difficult to design a system that can recover waste heat from all of these systems. Previous investigations have been conducted to solve this problem for various engines [10–15]. However, few of these investigations have concentrated on light-duty diesel engine applications.

In this paper, a dual loop ORC system is designed, combining a high temperature (*HT*) loop and a low temperature (*LT*) loop to simultaneously recover the waste heat from the exhaust, the intake air, and the coolant of a light-duty diesel engine. The *HT* loop recovers the exhaust heat, whereas the *LT* loop recovers the residual heat from the *HT* loop and the waste heat from both the intake air and the coolant. The two separate loops are coupled through a pre-heater. To evaluate the dual loop system performance when

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Nomenclature

$\dot{W}$	power (kW)
$\dot{m}$	mass flow rate (kg/s)
h	enthalpy (kJ/kg)
s	entropy (kJ/kg K)
$\dot{I}$	exergy destruction rate (kW)
T	temperature (K)
P	pressure (MPa)
$\dot{Q}$	heat quantity (kW)
mf	mass fraction
x, *y*	molar amount

Greek letters

η	efficiency

Subscript

cr	critical point
bp	normal boiling point
0	reference state
HT1,*HT2*,*HT2s*,*HT3*,*HT4*,*HT4s*	state points in *HT* loop
LT1,*LT2*,*LT2s*,*LT3*,*LTa*,*LT4*,*LTb*,*LT5*,*LT6*,*LT6s*	state points in *LT* loop
p1	pump 1
p2	pump 2
exh	exhaust gas
in	at the inlet
out	at the outlet
e1	evaporator 1
e2	evaporator 2
s1	expander 1
s2	expander 2
pre	pre-heater
int	intercooler
cool	coolant
c	*condenser*
mc	mean condensing temperature
me	mean evaporation temperature
f	fuel
a	intake air
b	brake
i	indicated
misc	miscellaneous
n	net
cs	combined system
HT	*HT* loop
LT	*LT* loop

Acronyms

ORC	organic Rankine cycle
HT	high temperature
LT	low temperature
ODP	ozone depletion potential (relative to R11)
GWP	global warming potential (relative to CO_2)
SUV	sport utility vehicle
bsfc	brake specific fuel consumption

combined with a light-duty diesel engine, the waste heat quantities are first calculated using engine test data. Based on these calculations, the working parameters for the *HT* and *LT* loops are determined. R245fa and R134a are selected as the working fluids for the *HT* loop and the *LT* loop, respectively. Finally, the performance map of the combined system is calculated and compared to a system with a non-bottoming ORC.

2. System design

The waste heat generated by a light-duty diesel engine is found mainly in the exhaust, the intake air, and the coolant. The waste heat carried by the lubrication system can be added to the coolant waste heat if a water-cooled heat exchanger is used. The dual loop ORC designed for this study is shown in Fig. 1. The *HT* loop recovers the exhaust waste heat, while the *LT* loop is coupled to recover the residual heat of the *HT* loop, the waste heat of intake air in the intercooler, and the coolant waste heat. The *HT* loop consists of a pump (pump 1), an evaporator (evaporator 1), an expander (expander 1), the pre-heater, a reservoir (reservoir 1), and the associated connecting pipes. The *LT* loop consists of a pump (pump 2), the intercooler, the pre-heater, an evaporator (evaporator 2), an expander (expander 2), the condenser, a reservoir (reservoir 2), and the associated connecting pipes. The *LT* loop is coupled to the *HT* loop via the pre-heater, which is used as the condenser for the *HT* loop. Two single screw expanders were adopted here, which were invented by Beijing University of Technology, China [16,17]. The working fluid of the *HT* loop was chosen to be R245fa because of its good safety and environmental properties [18]. For the low-temperature ORC, R134a was selected as the working fluid because of its appropriate critical temperature and pressure. R134a is also an environmentally friendly refrigerant with a zero ODP and a relatively low GWP value [19], widely used in automotive air-conditioners. The properties of these two working fluids are listed in Table 1.

The working principle of the dual loop system is illustrated in Fig. 2. After the light-duty diesel engine warms up, the ORC system starts to recover the waste heat. The R245fa is pumped from reservoir 1 to evaporator 1, corresponding to the *HT1* to *HT2* process. The waste heat from the exhaust is then added, and the working fluid is evaporated to the saturated vapor state, *HT3*. Subsequently, the R245fa is expanded through expander 1, and the useful work out is used to generate electricity. R245fa is a dry working fluid, therefore, it changes to the superheated state, *HT4*, after expansion. Upon reaching the pre-heater, the R245fa is transformed into the saturated liquid state, *HT1*, after transferring its heat to the R134a working fluid. Later, the working fluid returns to reservoir 1 and waits for the next circulation cycle. Meanwhile, in the *LT* loop, pump 2 pressurizes the R134a from reservoir 2 in preparation to be sent to the intercooler. The corresponding process is shown as moving from *LT1* to *LT2* in Fig. 2. The R134a is heated to the sub-cooled state *LT3* by the intake air in the intercooler. Subsequently, the R134a enters into the pre-heater and changes into the two-phase state, *LT4*. The coolant then flows out of the engine jacket and heats the R134a to the superheated state *LT5* inside of evaporator 2. Overheating is required because R134a is a wet working fluid and overheating guarantees that no liquid is generated during the subsequent expansion process. The R134a remains in the slightly superheated state *LT6* after undergoing an expansion process inside expander 2. Later, the fluid is condensed back to the saturated liquid state *LT1* in the condenser before flowing back into reservoir 2. The saturation curves of R245fa and R134a are plotted in the *T*–*s* diagram of Fig. 2. The upper red[1] lines correspond to the *HT* loop, while the lower blue lines show the *LT* loop.

[1] For interpretation of color in Figs. 2 and 3, the reader is referred to the web version of this article.